US ARMY RDECOM

U.S. Army Research, Development and Engineering Command

Mass Asymmetry and Tricyclic "Wobble" Motion Assessment

Using Automated Launch Video Analysis

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TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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PRESENTATION CONTENTS

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Measurement Methodology

Initial Mass Imbalance Test (June 2015)

Comparison of Results to Expected Values
- Includes follow-up test (February 2016)

Conclusions

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Background: Dynamic Imbalance

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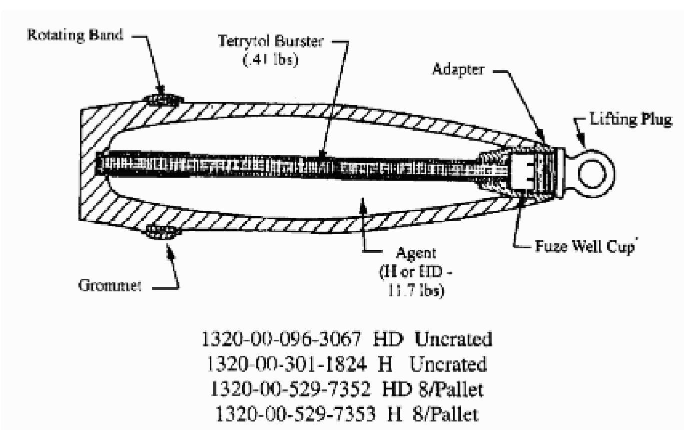
155mm M110A2E1 White Phosphorus (WP) Projectile

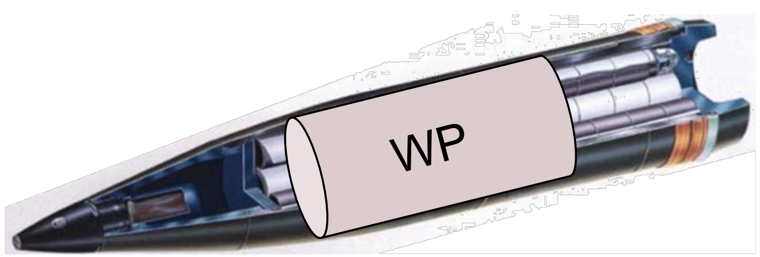
Theory:

If stored on its side at hot temperatures, the white-phosphorus (WP) fill will settle to one side, causing a permanent mass imbalance.

M110 155mm WP Projectile Shown

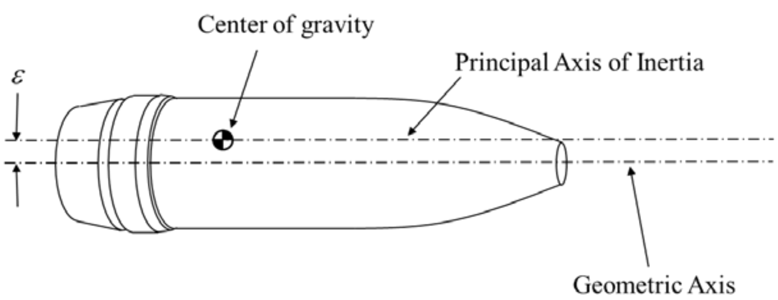


M110A2E1 version:
- canister of WP inside M483 155mm cargo shell

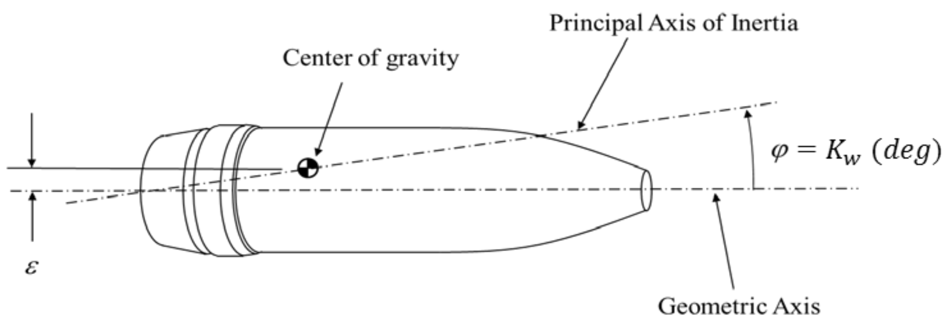


(All images taken from Globalsecurity.org)

Static Imbalance



Dynamic Imbalance



If this dynamic imbalance is sufficient, high values of angle-of-attack may result inducing tricyclic (“wobble”) motion.

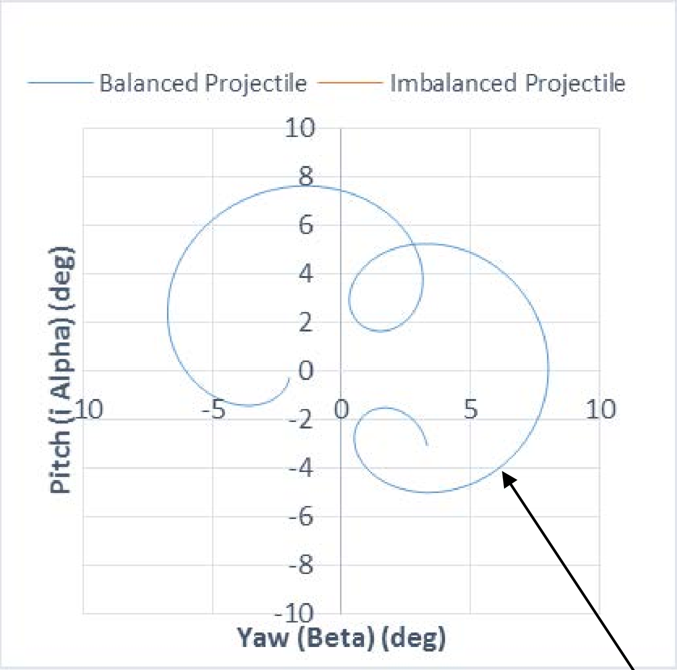
High values of angle-of-attack cause more drag on the projectile, resulting in losses in range.

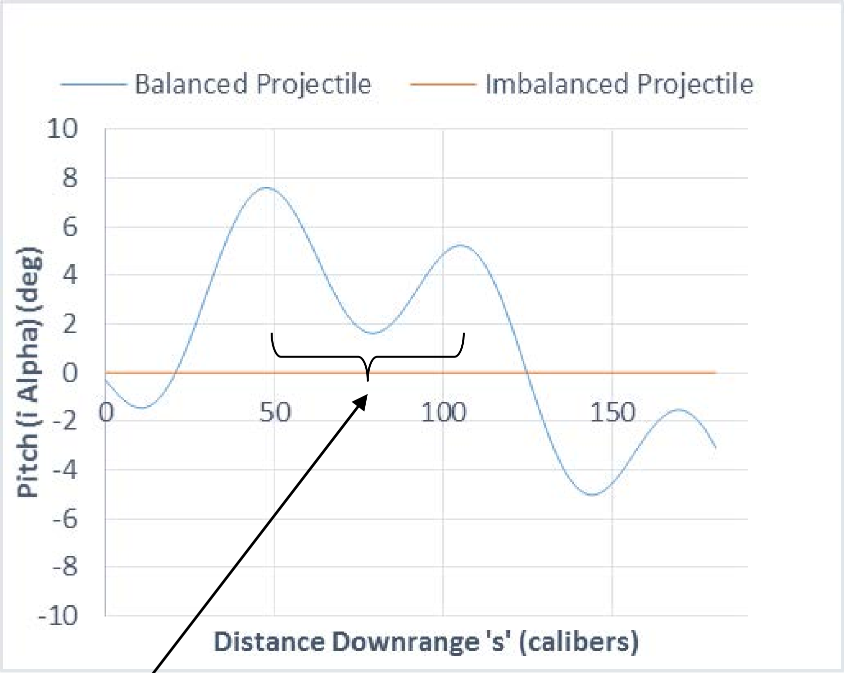
(from Carlucci & Jacobson, 2014, p. 334)

Axially Symmetric Epicyclic Motion

A symmetric spin-stabilized projectile "cones" around its velocity vector at two frequencies:

Fast Oscillation: Nutation
Slow Oscillation : Precession





nutation
cycle

Wobble Caused by Dynamic Imbalance

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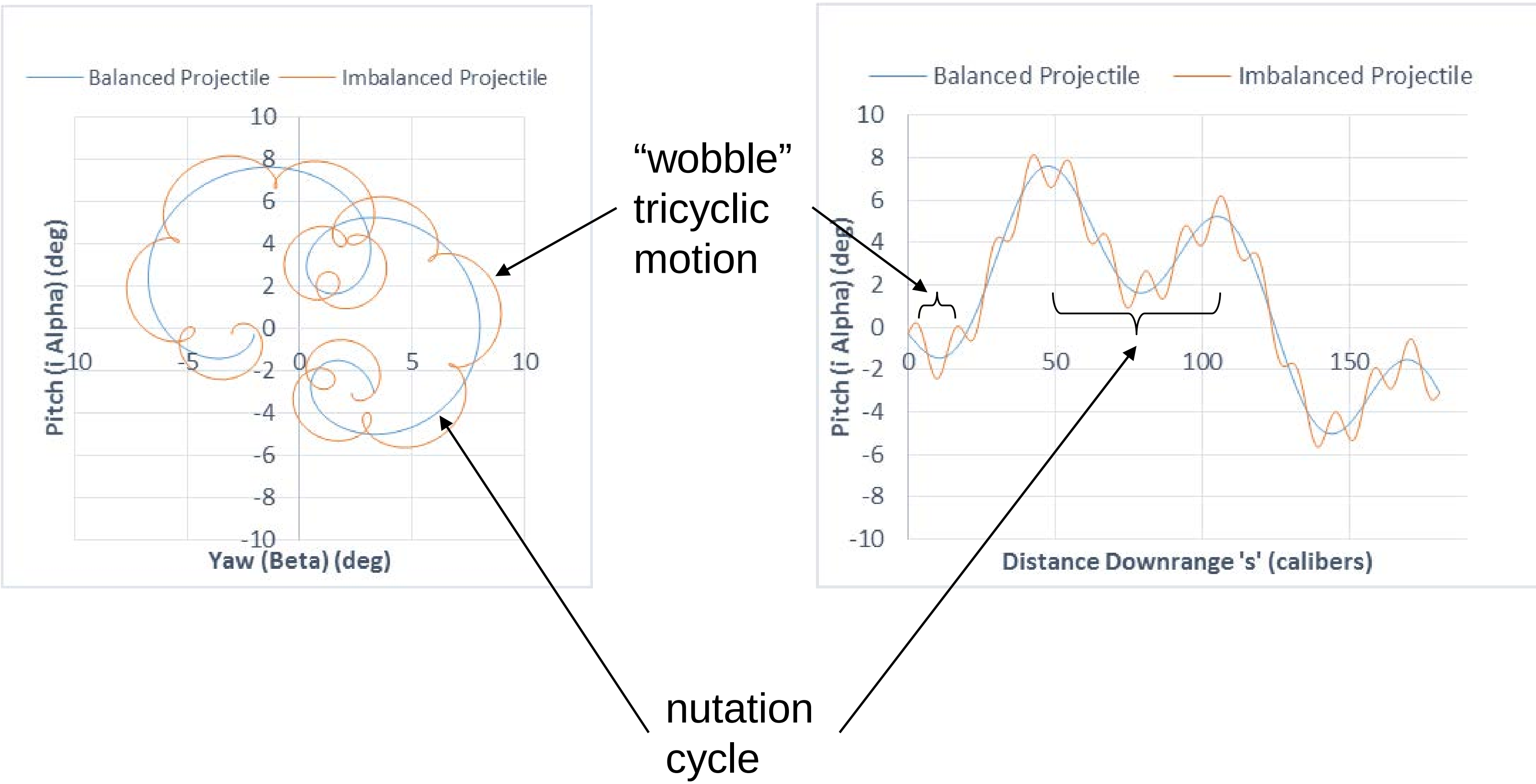
A projectile with a dynamic imbalance exhibits a third frequency relative to its geometric axis and occurring at the spin-rate



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Measurement Methodology

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Procedure Overview (3 Steps)

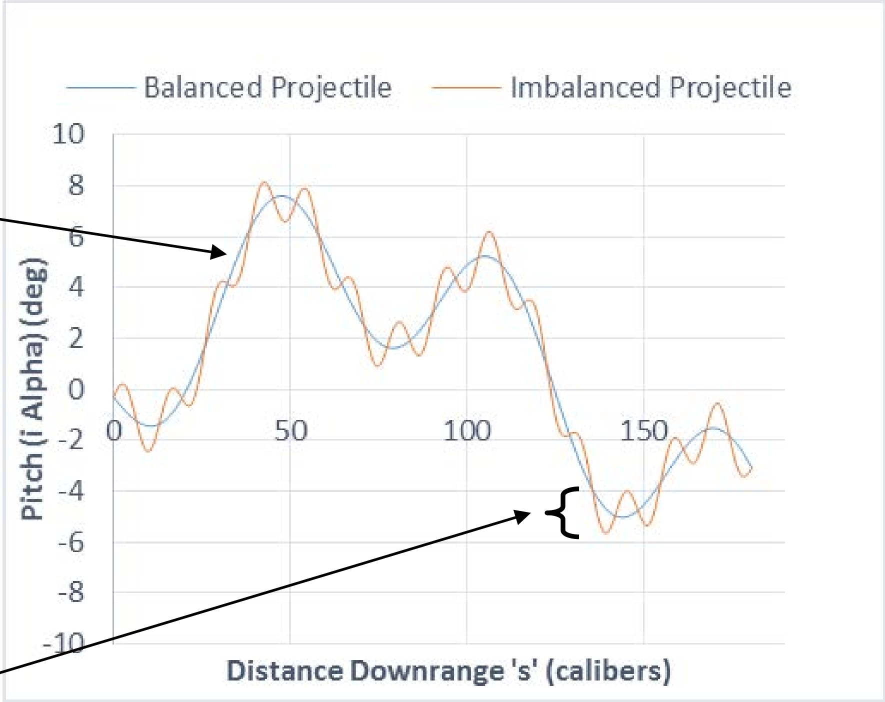
1) Measure Actual Orientation History

2) Fit & Subtract Undamped Epicyclic Motion

$$\alpha_{pitch} = Fast\_Oscillation + Slow\_Oscillation$$

$$\alpha_{pitch} = K_F \cos\left(\phi_{F0} + \dot{\phi}_F (x - x_0)\right) + K_S \cos\left(\phi_{S0} + \dot{\phi}_S (x - x_0)\right)$$

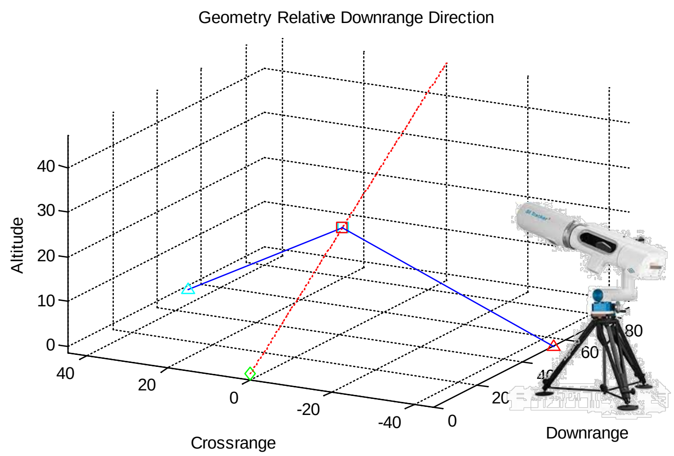
x − downrange distance traveled (or time)
$K_{F,S}$ − magnitudes of the fast and slow oscillations
$\Phi'_{F,S}$ − frequencies of the fast and slow oscillations
$\Phi_{0F,0S}$ − phase shifts of the fast and slow oscillations
(McCoy 2009)

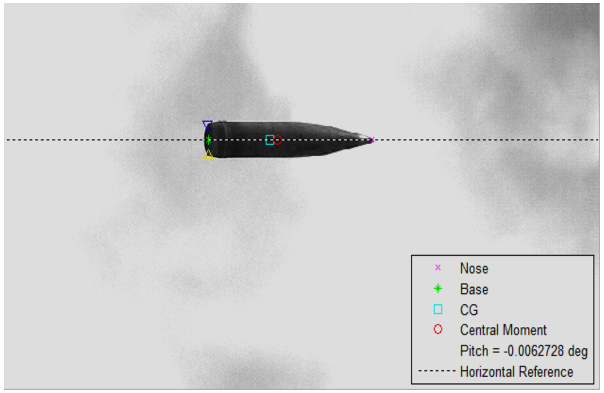


3) Measure magnitude of the wobble motion

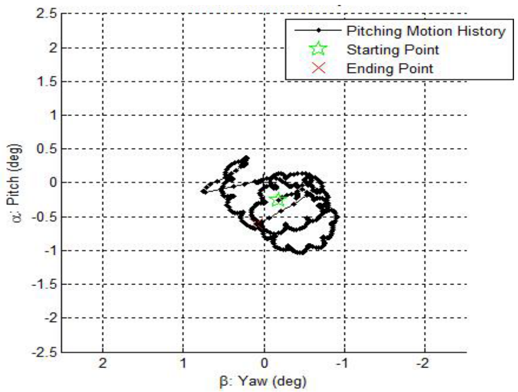
Wobble Motion Measurement

1) Measure Orientation history: Use Automated Flight Video Analysis (AFVA) to Measure Projectile Orientation





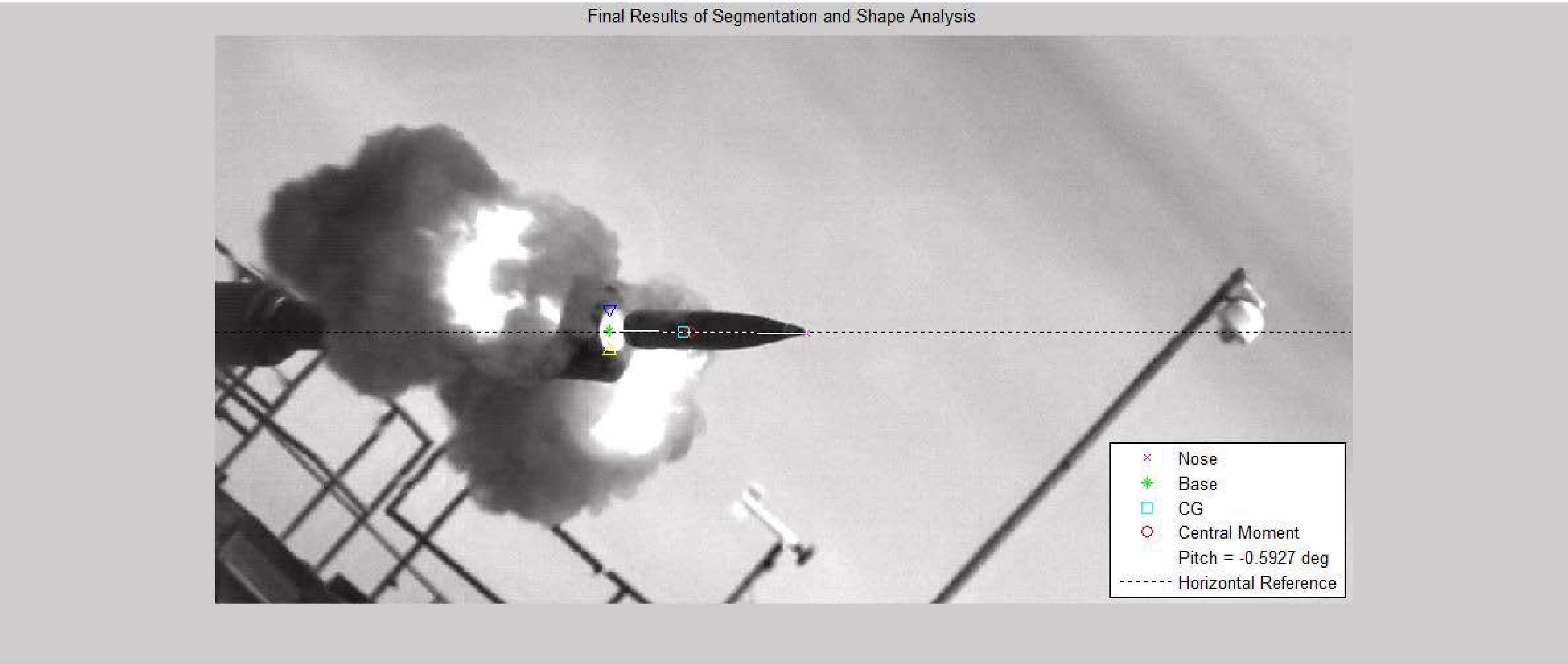
Resolve 3D Orientation History Motion



Process video from camera system on both sides of gun

(Decker 2013)

Automated Launch Video Demo: June 2015 M110A2E1 Test

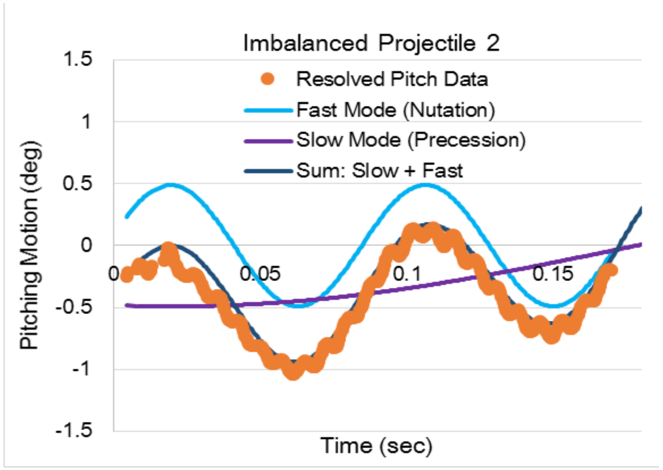


Wobble Motion Measurement

2) Manually Fit Undamped Epicyclic Motion to Data

$$\alpha_{pitch} = K_F \cos\left(\phi_{F0} + \dot{\phi}_F (x - x_0)\right) + K_S \cos\left(\phi_{S0} + \dot{\phi}_S (x - x_0)\right)$$

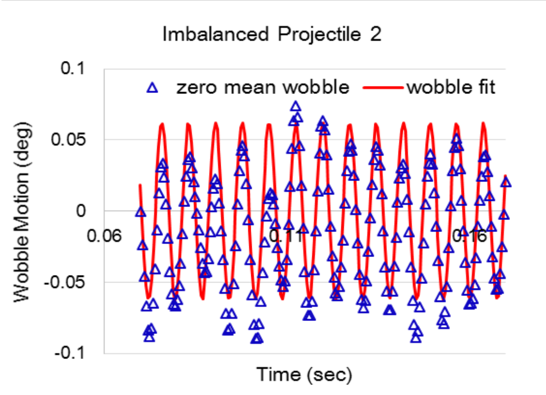
x – downrange distance traveled (or time)
$K_{F,S}$ – magnitudes of the fast and slow oscillations
$\Phi'_{F,S}$ – frequencies of the fast and slow oscillations
$\Phi_{0F,0S}$ – phase shifts of the fast and slow oscillations



3) Manually Fit Sinusoid to Wobble Motion

$$K_W \sin\left(\phi_{W0} + p \cdot t\right)$$

K_W, is the wobble amplitude
φ_{W0} is the wobble motion phase shift
p is the projectile's spin rate (known from muzzle velocity)
t is time



M110 A2E1 Mass Asymmetry Test
June 2015 – Yuma Proving Grounds, AZ

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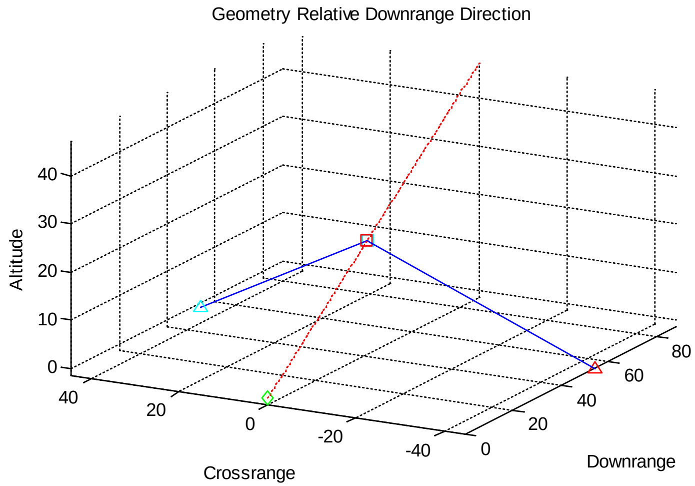
Sample Results: Shot 325

Eight projectiles stored on their side at 140ºF to induce asymmetry of WP

Four of those projectiles were then re-melted to restore “normal” asymmetry conditions

Range Setup:



QE = 500mils (4 Shots Each)
Firing Azimuth = 86.5º (ENE)
Effective Crossrange Offset = 45m
Effective Downrange Distance = 54m (to trunnion)
Muzzle Velocity: 430m/s

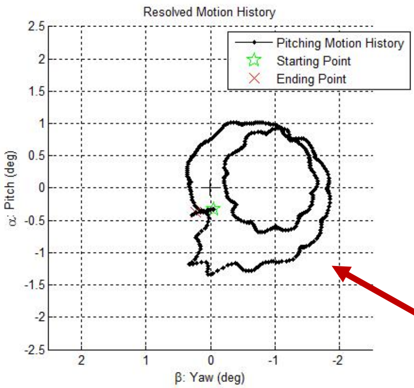
Dual Trajectory
“Tracker 2” Systems

Photron Fastcam SA-X2
Color Camera
w/ 300mm telephoto lenses
recorded at: 2000hz

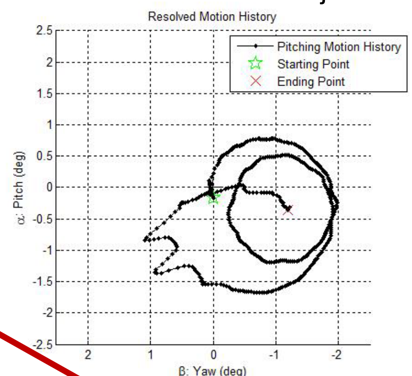
Tests Results: Alpha-Beta Plots

Pair 1

Asymmetric Projectile

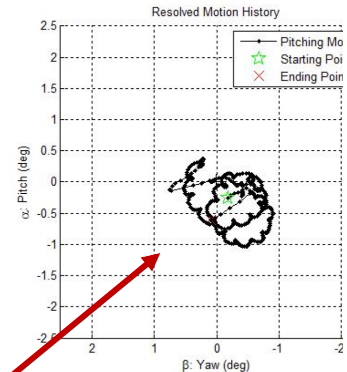


Balance-Restored Projectile

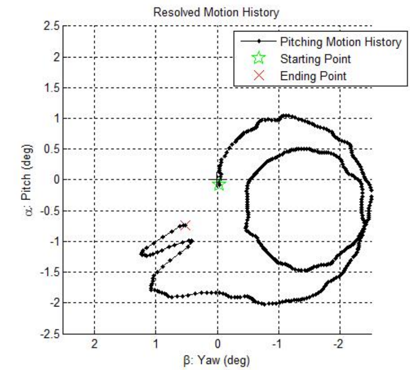


Pair 2

Asymmetric Projectile



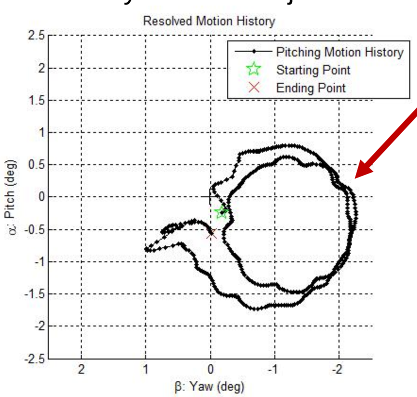
Balance-Restored Projectile



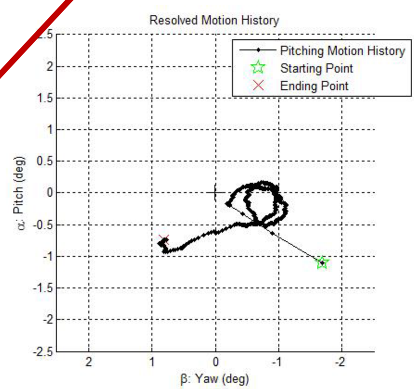
Asymmetry Clearly Evident

Pair 3

Asymmetric Projectile

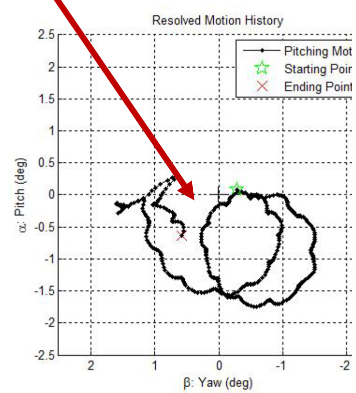


Balance-Restored Projectile

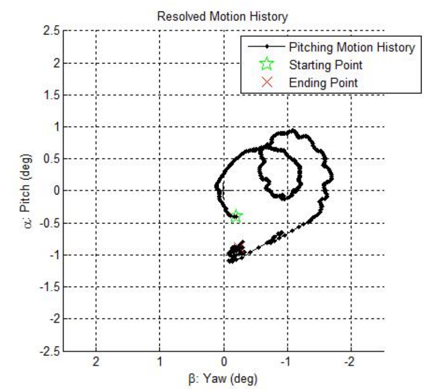


Pair 4

Asymmetric Projectile

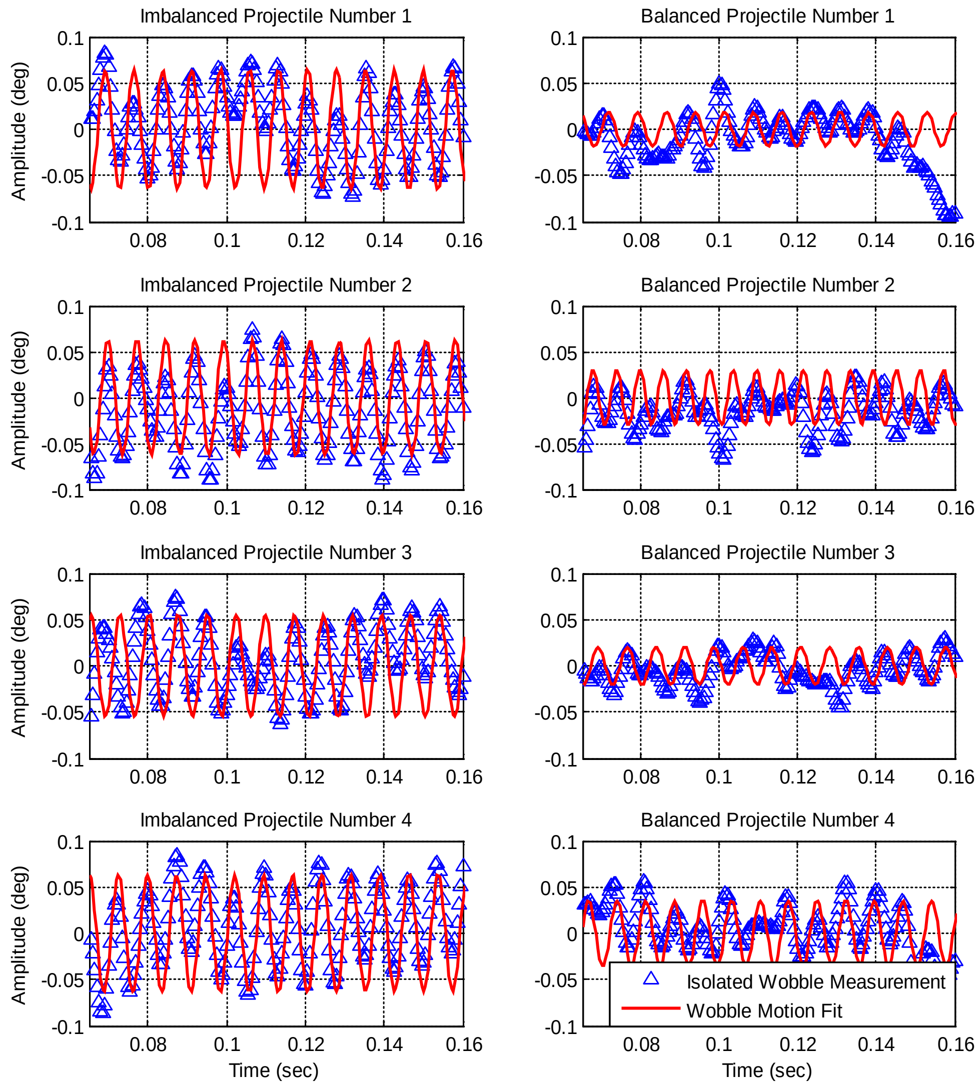


Balance-Restored Projectile



Extracted Wobble Motion Plots

Imbalanced Projectiles | Balance-Restored Projectiles



Comparison to Predicted Results

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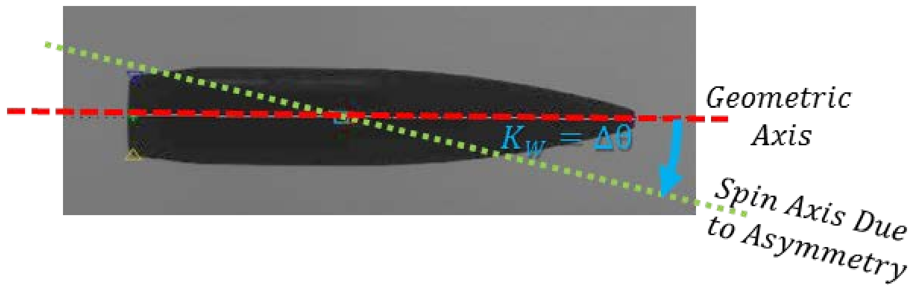
Predicted Wobble Motion



Prediction Model:

$$K_w(rad) = \frac{I_E}{I_T - I_P + \left(\frac{I_P^2 M}{I_T P^2}\right)} \approx \frac{I_E}{I_T - I_P}$$

(McCoy, 1999, p. 259)

Term is relatively small

I_P is the inertia along the projectile spin axis
I_T is the transverse moment of inertia
I_E is the product of inertia resulting from the mass asymmetry.

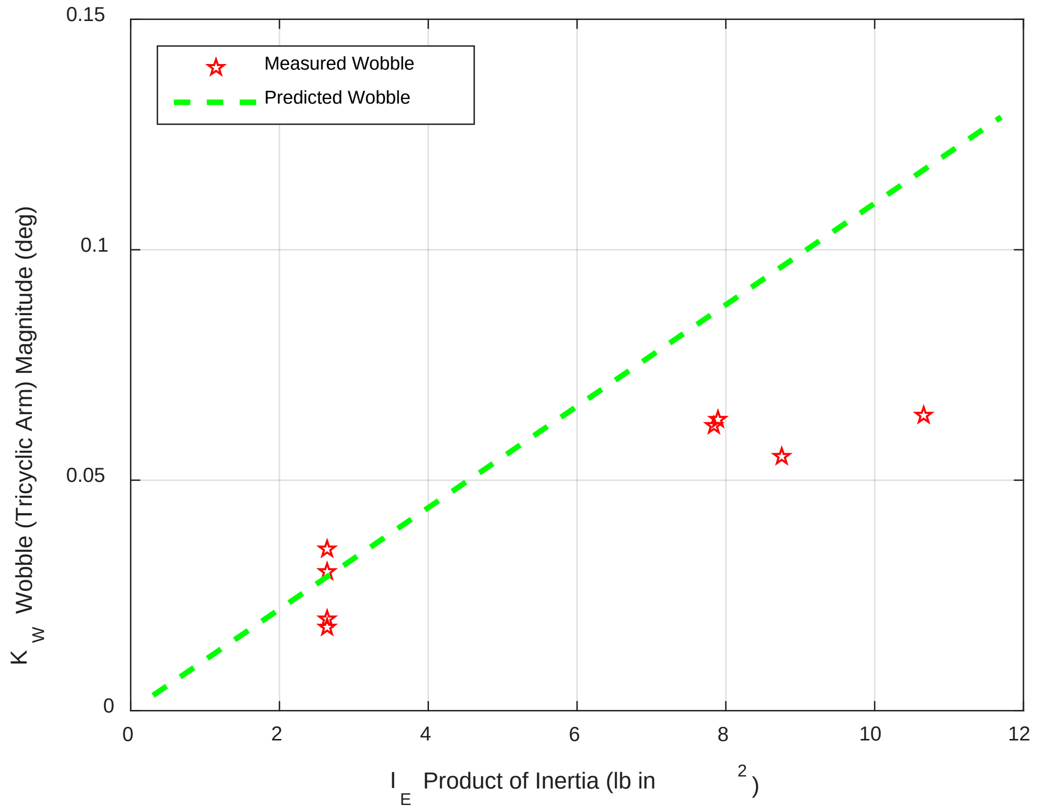
M110A2E1 Average Values:
I_T=5755 in^2lb
I_P=555 in^2lb

$$K_w(deg) = \frac{I_E}{I_T - I_P} = \frac{I_E}{5755 - 555}\left(\frac{180}{\pi}\right) = \frac{I_E}{90.8\frac{deg}{in^2 lb}}$$

Results VS. Predicted Values (JUNE 2015 Test)

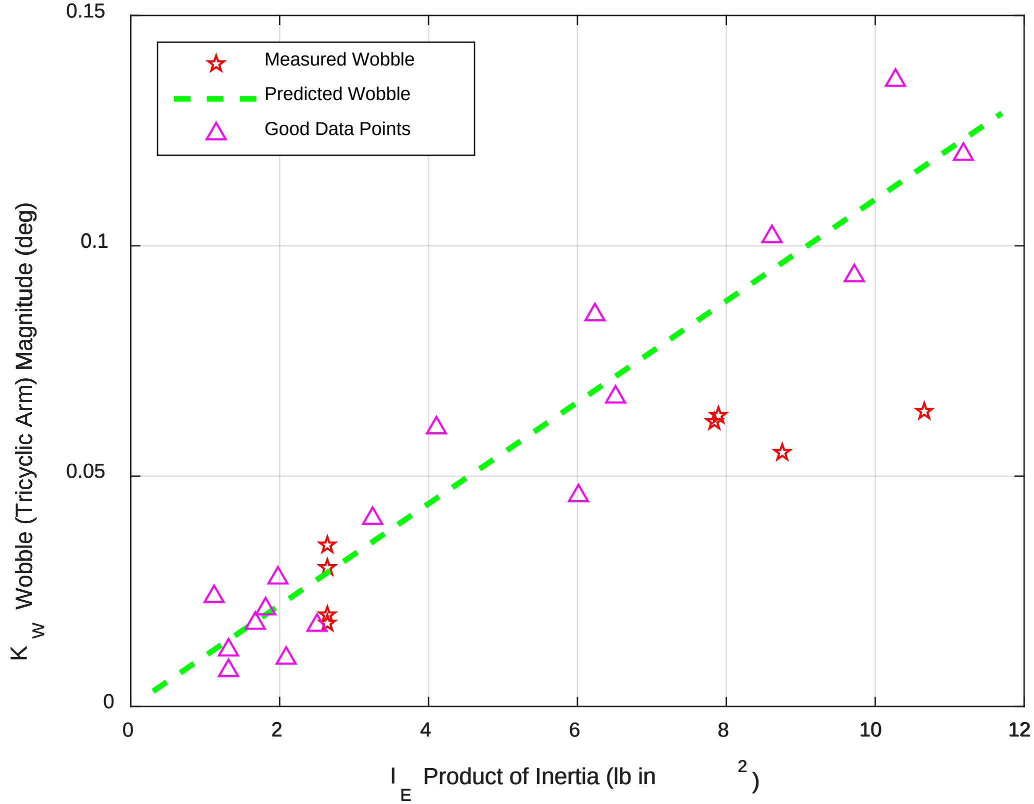
Re-balanced projectiles were not re-measured for June 2015 test

(predicted wobble estimated based on average values for M110A2E1)



Results VS. Predicted Values (Good Data Points February 2016 Test)

Follow-up Test (Feb 2016)
17/30 Shots: within 0.025º of predicted value for K_W



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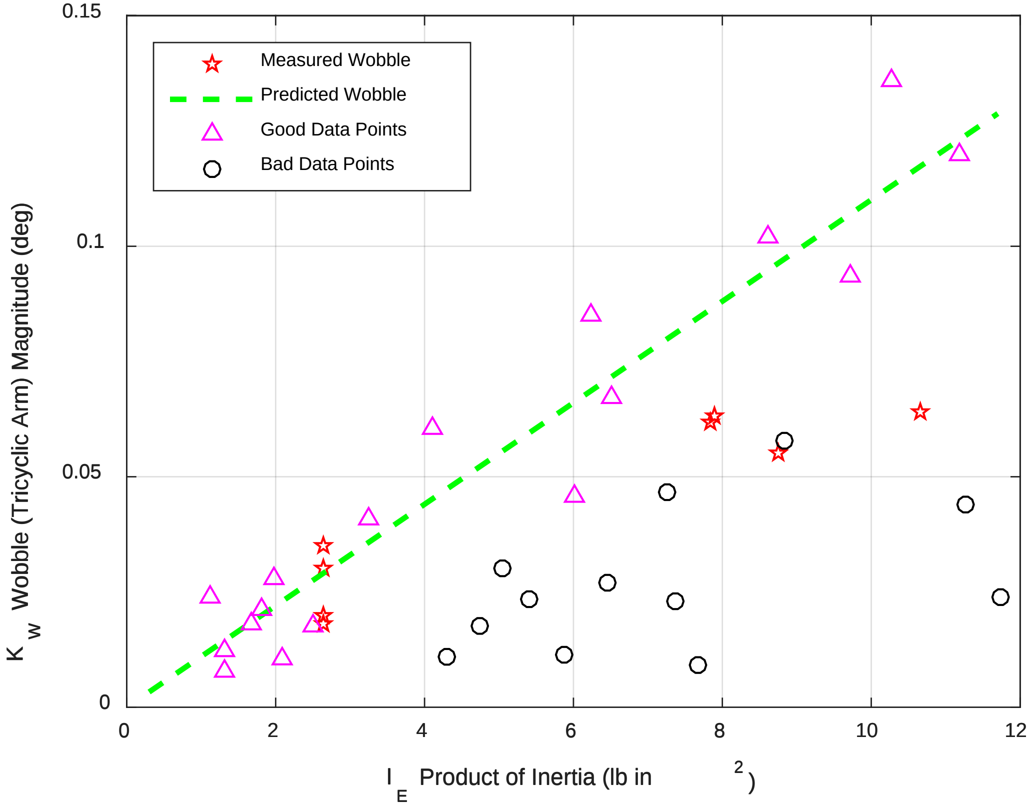
RESULTS VS. PREDICTED VALUES (ALL DATA POINTS FEBRUARY 2016 TEST)

13/30 shots exhibited lower than expected wobble

-may or may not indicate re-settling of WP asymmetry occurred (possibly during setback of cannon launch)



Conclusions

- High quality video was successfully captured for all test rounds (including follow-up test) allowing for data analysis
- All white-phosphorous projectiles flew with stability, despite concern of tumbling
- The effect of mass asymmetry is clearly evident
  - Indicates that the Automated Flight Video Analysis (AFVA) method is sensitive to minute fluctuations ($<0.01^0$) in pitch/yaw motion
  - Indicates that the Automated Flight Video Analysis (AFVA) system is capable of measuring these fluctuations within 0.025^0
  - Quantifying mass asymmetry from flight video seems plausible
  - Suggests significant advantage over rough precision of yaw-card analysis and high cost of on-board electronics systems
- This precision of pitch/yaw (initial) history measurement should be helpful to other programs

References

1. Carlucci, D. and Jacobson, S., "Ballistics: Theory and Design of Guns and Ammunition," CRC Press, Boca Raton, FL, 2008.
2. McCoy, R., "Modern Exterior Ballistics: The Launch and Flight Dynamics of Symmetric Projectiles," Schiffer Publishing, Atglen, PA, 1999.
3. Koenig, W., "M110A2E1 Aero Predictions," Aeroballistic Simulations, U.S. Army Armament Research, Development, and Engineering Center, Picatinny Arsenal, NJ, March 2015. (limited distribution)
4. Decker, R., Kolsch, M., and Yakimenko, O.A., "A Computer Vision Approach to Automatically Measure the Initial Spin-Rate of Artillery Projectiles Painted with Stripes," *JOTE* 42(4):828–841, July 2014.
5. Decker, R., "A Computer Vision-Based Method for Artillery Characterization," Doctoral Dissertation, Naval Postgraduate School, Monterey, CA, December 2013. (limited distribution)
6. John, J., "M1122, M483, M110A2E1 Mass Properties and POIs," Measurement Data, U.S. Army Armament Research, Development, and Engineering Center, Picatinny Arsenal, NJ, June 2015. (limited distribution)
7. M110 Projectile Images accessed from GlobalSecurity.org, March16, 2016. http://www.globalsecurity.org/military/systems/munitions/m110.htm
8. DeMella, D. and Ackerman, E., "155MM Artillery Weapons Systems Reference Data Book," U.S. Army Armament Research, Development, and Engineering Center, Picatinny Arsenal, NJ, May 2009. (limited distribution)

Questions?

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Backup Slides:
Automated Measurement Methodology
(February 2016)

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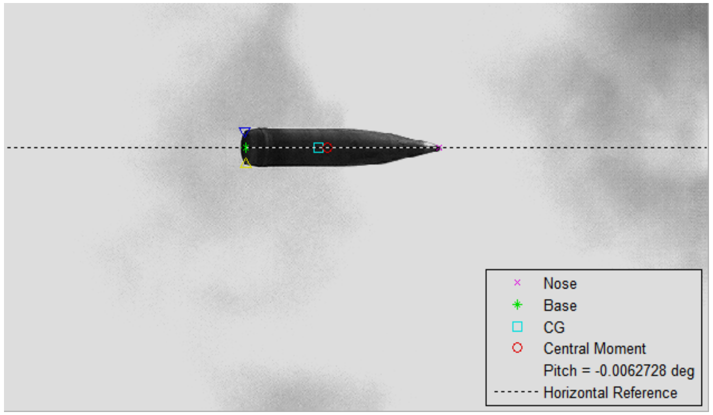
New Automated Data-Extraction Method



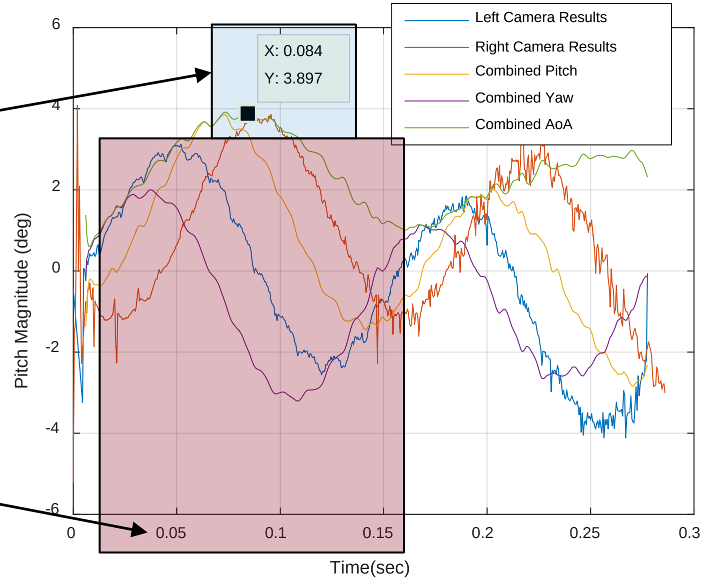
1) Analyze Pitching Motion Using ALVA

(Decker 2013)

2a) Measure FMY and choose best data source for epicyclic fitting

-which camera's data was best?

-during what time interval was data of sufficient quality



2b) Perform a initial fit to identify candidate combinations for <u>damped</u> epicyclic parameters

MACS 1: V_{MUZZLE} = 286 m/s		
ϕ'_F	7.0	Hz
ϕ'_S	1.4	Hz
λ_F	-1.6	deg/s
λ_S	-21.8	deg/s

M203A1 : V_{MUZZLE} = 788 m/s		
ϕ'_F	20.0	Hz
ϕ'_S	3.7	Hz
λ_F	-88.4	deg/s
λ_S	-58.0	deg/s

(Koenig 2016)

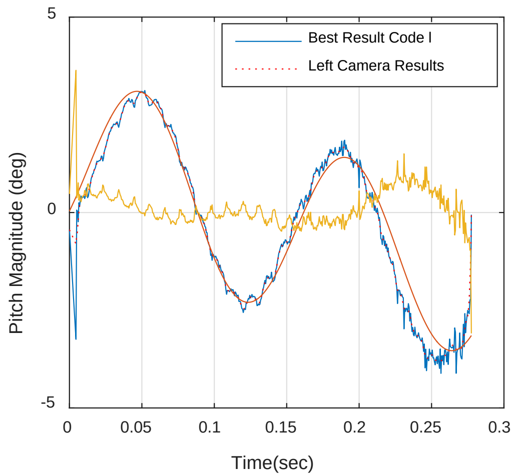
$$\alpha_{pitch,damped} = K_F e^{-\lambda_F (x-x_0)} \cos\left(\phi_{F0} + \dot{\phi}_F (x-x_0)\right) + K_S e^{-\lambda_S (x-x_0)} \cos\left(\phi_{S0} + \dot{\phi}_S (x-x_0)\right)$$

K_F, K_S, are the fast and slow epicyclic oscillation magnitudes
φ_{F0}, φ_{S0} are the fast and slow oscillation phase shifts

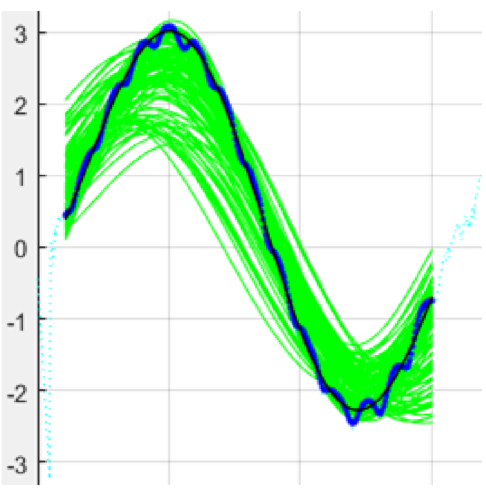
$$\left.\begin{array}{l}\varphi'_F,\ \varphi'_S \text{ are the fast and slow epicyclic frequencies} \\ \lambda_F,\ \lambda_S, \text{ are the fast and slow oscillation damping rates}\end{array}\right\} \text{known values for given velocity}$$

2c) Robust Fit: Artificially increase K_F, K_S, and decrease φ'_F, φ'_S , then perform least-squares fit to smoothed data in region of highest data fidelity (best complete peak)

TRN 2397



TRN 2397



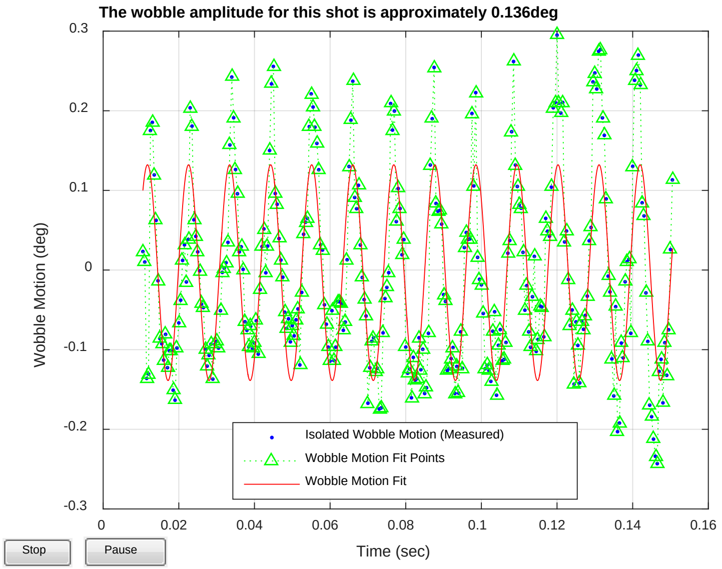
2d) Subtract raw UNSMOOTHED pitch measurements from epicyclic fit

$$K_W \sin(\phi_{W0} + p \cdot t) + C_1$$

K_W, is the wobble amplitude
φ_{W0} is the wobble motion phase shift
p is the projectile's spin rate (known from muzzle velocity)
C_{1s} is the offset from the horizontal axis due to errors in epicyclic motion fitting
t is time

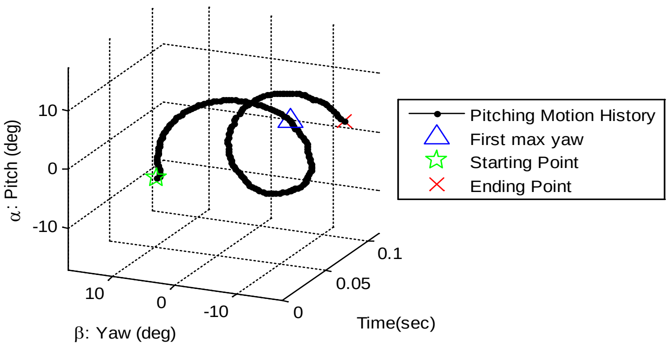
3) Automatically fit a shifted sinusoid to the resulting motion. The amplitude of this fit is K_W

TRN 2397

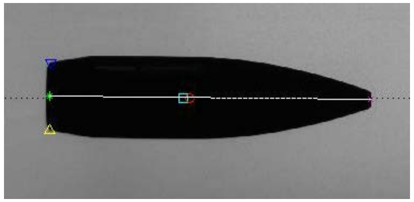


- Mechanical Engineer
  - US Army ARDEC Fuze & Precision Armaments Technology Group

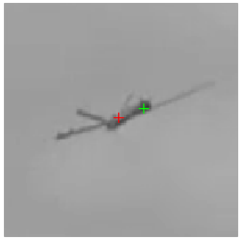
- Developed automated analysis algorithms:
  - Artillery flight video analysis (AFVA)
    - Position / velocity
    - Initial orientation (pitch/yaw) history
    - Spin-rate analysis
    - Shape transformation analysis



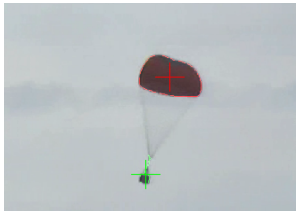
  - Additional aerial platforms



Small Caliber Ammo



UAV Tracking



ADS Tracking

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